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AN OPTICALLY CONTROLLED DIFFUSE DISCHARGE SWITCH*

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Abstract

Theoretical investigations of an optically controlled plasma switch in a divertor circuit show that significant power amplification can be expected by using appropriate gas mixtures in a high pressure, (≈ 1 atm) volume discharge. Controlled increase of plasma conductivity is obtained by two-step photoionization of excited molecules using a high power visible laser. Admixtures of an electronegative gas cause a rapid decline of conductivity due to electron attachment after laser turn-off. Further reduction of the switch opening time can be obtained either by additional optical excitation of strongly attaching vibrationally excited molecules or by using attachers with attachment rates increasing with rising field strength. An experiment was designed to produce diffuse discharges at atmospheric pressure suitable for testing optogalvanic and attachment effects. Temporal stability and spatial homogeneity dependent on the type of electronegative gas and its concentration will be studied using electrical and optical diagnostic techniques. The investigations are considered as a first step towards an optically controlled rep-rated switch with opening times in the order of 10 ns.

Introduction

Energy storage using inductive elements is attractive in pulse power applications because of its intrinsic high energy density, some 10^2 to 10^3 times higher than for capacitive storage[1]. A major obstacle in the advancement of this technology is the development of an opening switch capable of repetitive operation without the need for replacing the switching medium after every shot.

Two concepts seem to be particularly attractive, the electron beam controlled switch and the optically controlled switch. In the case of an electron-beam controlled switch a diffuse discharge is sustained by collisional ionization and a reduction of conductivity is obtained after turn off of the electron beam by electron attachment processes in a gas with small admixtures of an electronegative gas[2]. A similar concept can be used for a laser controlled switch. But in addition a laser offers the possibility of using resonant processes to change the conductivity of a diffuse plasma.

The laser power or the electron-beam power necessary to sustain a diffuse discharge in a gas mixture containing an attacher, is:

$$P = n_e V E_{ion} \frac{1}{T_{op}}$$

where n_e is the electron density of the plasma, V the discharge volume, E_{ion} a characteristic ionization energy, and T_{op} the time necessary to replace the electrons lost by attachment and recombination processes. T_{op} can be considered the opening time of the switch.

For an opening switch, where the opening mechanism is based on dissipation processes - attachment and recombination - there is always a trade-off between opening time T_{op} and laser or electron-beam power. The shorter the opening time, the higher the power necessary to sustain a diffuse discharge and consequently the greater the heating effects in the plasma. Thus, it is important to look for mechanisms in the attachment process which can be used to overcome this disadvantage.

Resonance Dissociative Electron Attachment

For an attachment dominated switch the time constant for replacement of the electrons, T_{op}, is given by:

$$\frac{1}{T_{op}} = kn_A ,$$

where k is the attachment rate coefficient and n_A the concentration of the electronegative gas in the switch. To reduce losses during conduction (the "on"-state), but on the other hand to guarantee fast opening, the attachment rate coefficient should have a low value during the "on"-state of the discharge. It should have a high value when fast reduction of the electron density is needed, i.e. during the opening phase. To control the attachment rate coefficient or the attachment cross section, respectively, a well-known property of an attacher can be used: the dependence of the attachment cross-section on the electron energy for resonant dissociative electron attachment.

The mechanism of resonant dissociative electron attachment can be understood by considering the potential energy diagrams of attaching diatomic molecules. In Fig. 1 a general type of dissociative electron attachment process is illustrated. The potential energy curve of a neutral diatomic molecule AG is crossed at an energy E_ν^* above the ground state by a repulsive potential energy curve of the negative ion AB^-. Resonance associative attachment can be considered to proceed in two steps[3]:

$$e + AB \longrightarrow AB^{-*} \longrightarrow A + B^-$$

The first process occurs by collisional excitation - including attachment - from the ground state to the excited state according to the Franck-Condon principle. The resulting compound system AB^{-*} dissociates then into the final products A and B^-.

Only electrons within a restricted energy range around E_e^* - the energy of the vertical transition - are able to excite the neutral attacher molecule. Thus the attachment cross section should have a maximum[4] for electron energies of E_e^*. The energy of the vertical transition E_e^* varies, depending on the attacher, from ∿ 0 to 15 eV. According to these considerations it should be possible to tailor the attachment cross sec-

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14. ABSTRACT
Theoretical investigations of an optically controlled plasma switch in a divertor circuit show that significant power amplification can be expected by using appropriate gas mixtures in a high pressure, (~ 1 atm) volume discharge. Controlled increase of plasma conductivity is obtained by two-step photoionization of excited molecules using a high power visible laser. Admixtures of an electronegative gas cause a rapid decline of conductivity due to electron attachment after laser turn-off. Further reduction of the switch opening time can be obtained either by additional optical excitation of strongly attaching vibrationally excited molecules or by using attachers vlith attachment rates increasing with rising field strength.

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tion curve for specific purposes using mixtures of gases.

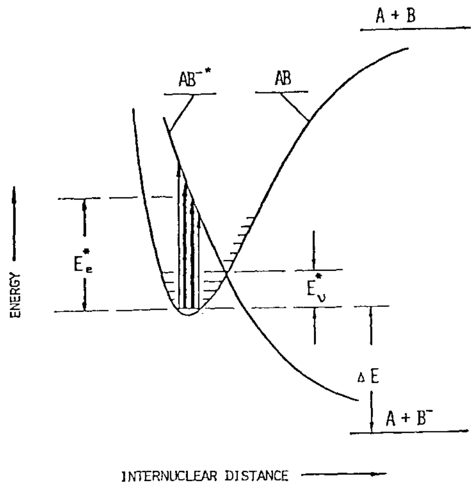

Fig. 1 Resonance Dissociative Electron Attachment

Divertor Circuit Performance

During the opening phase the voltage across the switch is increasing, i.e., E/N increases. E/N in turn determines the mean energy of the plasma electrons. To get a high attachment rate during opening and low attachment rate during the "on"-state it is necessary to choose an attacher or a combination of attachers with a small attachment cross section at low electron energies and a sharp rise at electron energies beyond the point of operation during the "on"-state. In such a system a feedback effect sets in once the electron production is decreased, independent of the way the discharge was sustained. The electron density is immediately reduced by attachment processes, causing an increase in resistance and, due to the dynamics of the circuit, the voltage in the switch increases. This in turn gives rise to an enhanced attachment, which causes a further increase in resistivity etc. The feedback effect should cause a rapid increase of switch resistance, which means rapid opening.

To simulate the opening phase of a switch as part of a divertor in an inductive circuit, a computer code (SCEPTRE) capable of treating time dependent circuit elements was used. The operation of the circuit shown in Fig.2 is as follows: the energy stored in the capacitor C is transferred to the inductor L upon closure of switch α. Subsequently, switch α is opened and switch β is closed, thus effecting the transfer of the energy stored in the inductor to the load R_L.

The component values shown in Fig.2 are reasonable for laboratory experiment. Switch α is the opening switch and switch β is assumed to be one which closes in a short time with small jitter. The buffer gas, the major constituent of the gas mixture in the opening switch was assumed to be N_2 for which the electron mobility is known. The operating point of switch α was set by taking the electric field to gas density ratio (E/N) to be 2 Townsend when the switch was on. For a switch with 25 cm^2 electrodes, spaced 1 cm apart and a gas pressure of 1 atmosphere this corresponds to about 0.5 kV between the electrodes. Under these conditions the current in the gap is about 1 kA.

Calculations were performed for three attachers[5] with different attachment rate coefficient characteristics to demonstrate the "feedback" effect (Fig.3). As

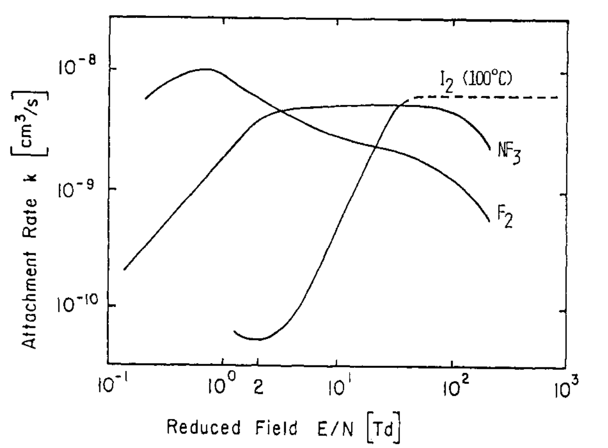

Fig. 3 Reduced Field Dependence of Attachment Rate[5]

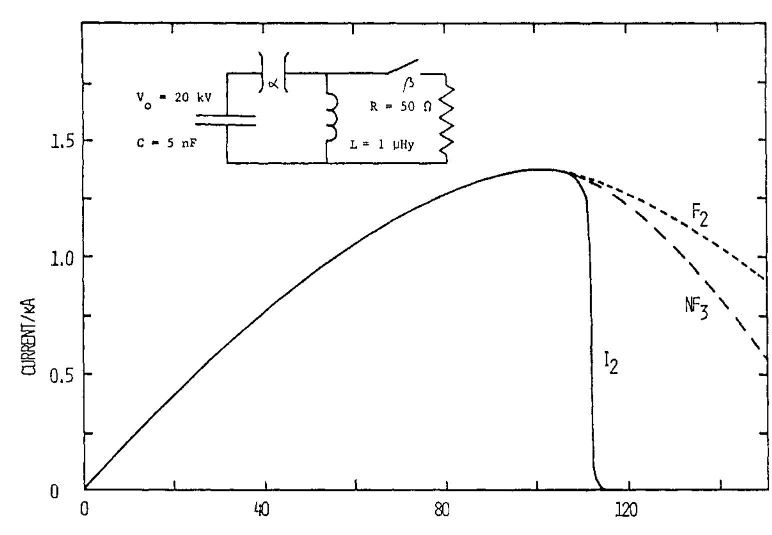

Fig. 2 Time-Dependence of Current Through Opening Switch in a Divertor Circuit

an example of gases with decreasing attachment rate coefficient k as a function of E/N we used F_2 (SF_6 belongs to this type of attachers), NF_3 was chosen as an example of constant k in the range of possible values of E/N, and I_2 as example of an attacher with strongly increasing k. Experimental results for I_2 exist up to E/N=50 Td. A constant value of k was assumed for reduced field strengths above 50 Td. In each case the product of the electron attachment rate coefficient and the attaching gas density, kn_A, was assumed to be $5.10^7\ s^{-1}$. This requires a pressure of only a few Torr of the attaching gas. Also, the electron density in the discharge during the on time was taken to be constant. The results for the current are shown in Fig.2. The use of I_2 results in a rapid current decrease in the switch compared with the other attaching gases. This agrees with the qualitative arguments given above, stressing the importance of the variation of the attaching rate with E/N.

Laser Controlled Discharge

The use of this inherent attachment "feedback" effect requires a diffuse, cold discharge during the "on"-state. If the generation of electrons during the "on"-state is controlled by a laser, there are two concepts which can be applied: First, the discharge is not self-sustained and the laser serves to sustain it (i.e. by means of multiphoton ionization of an organic gas). Secondly, the discharge is self-sustaining. The laser now serves as an agent for changing the conductivity from a highly resistive state ("off") to a low resistance state ("on") and vice versa. In this case the diffuse discharge is sustained by other means. We concentrated on the second concept, because of the possibility of using resonant effects (optogalvanic effects) in a photon energy range where high power, wide range tunable, long pulse duration lasers are available (dye-lasers).

The experimental arrangement for testing this concept is shown in Fig.4. A coaxial line is charged up to a voltage greater than the breakdown voltage of the opening switch 0. The voltage is applied to the opening switch through a laser-triggered[6] spark gap C. A few nanoseconds before the voltage is applied, the cathode of switch 0 is irradiated by means of a flash lamp through a metallic mesh which serves as the anode. The photoelectrons released from the cathode form a homogeneous layer guaranteeing the development of a homogeneous broad discharge[7]. To avoid instabilities

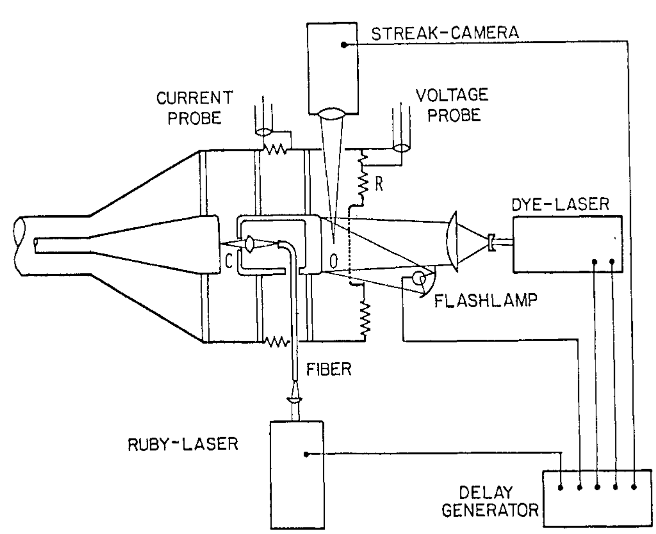

Fig. 4 Experimental Setup

extending from the cathode, a Rogowski-type electrode shape was designed according to the boundary conditions of the discharge chamber using a field plotting computer code. The discharge current can be controlled by means of a variable water resistor, R. Measurements of current and voltage across the gap and optical measurements by means of a streak camera are planned to get information on the stability of the diffuse discharge and its resistance.

After a diffuse discharge is initiated a dye-laser will be used to enhance the plasma conductivity. At first a combination of the following gases will be used N_2 (p=1 atm) as the buffer gas, a small percentage of NO, and a small percentage of I_2 or another attacher with the desired E/N dependence of the attachment rate coefficient.

Figure 5 shows an energy level diagram with the pertinent transitions in the system N_2, NO and I_2. The most important process is the two-step photoionization from an excited NO* state ($A^2\Sigma^+$) via an intermediate state ($E^2\Sigma^+$). This process is resonant, which means that almost all the laser energy is used for ionization. N_2 as the buffer gas has, besides its good dielectric strength, the advantage that the large population of the collisionally excited metastable state N_2 ($A^3\Sigma_u^+$) serves as an energy reservoir for the ionization process. Collisions of the second kind with a very high transition rate provide for population of the NO^* state, necessary for a high laser induced ionization rate.

The electrons produced by two-step photoionization are continuously removed by attachment processes. To keep the system in a highly conductive equilibrium state (the "on"-state) laser energy has to be supplied continuously. Once the laser is turned off, the electron density decreases and with the appropriate attacher a "feedback" effect sets in which provides the desired short opening times. To get more quantitative information on the dynamic behavior of this system as part of a divertor circuit, a kinetic model has been developed, with a computer program which includes 15 reactions.

Laser Induced Opening

Instead of using the laser to sustain the discharge during the conduction phase, it is possible to use it to increase the attachment cross section during the opening phase. This mechanism again can be understood by considering the potential energy curves of an attacher (Fig.1). One way of producing the excited negative ion compounds AB^{-*} is to use collisional excitation with electrons of sufficient energy E_e^* according to the Franck-Condon principle. A second way is the excitation of vibrational states of the molecule AB near the curve crossing point. The probability of attachment and succeeding dissociation is higher when the energy state of the vibrationally excited molecules is nearer the curve crossing.

Increased population of vibrational levels can be obtained by raising the temperature of the gas. This explains the strong temperature dependence of the attachment cross section for gases like I_2, where the curve crossing is near the 5th vibrational level of the neutral molecule[8]. It is important that the same result can be obtained by optical vibrational excitation using an IR laser. Using this method an increase in attachment cross section of several orders of magnitude can be obtained. For HCl molecules calculations have been performed[9], based on measurements of attachment cross sections as a function of temperature[10], which show an increase in cross section from 10^{-17} cm^2 for the v=0 vibrational level to 10^{-14} cm^2 for v = 2 (Fig. 6).

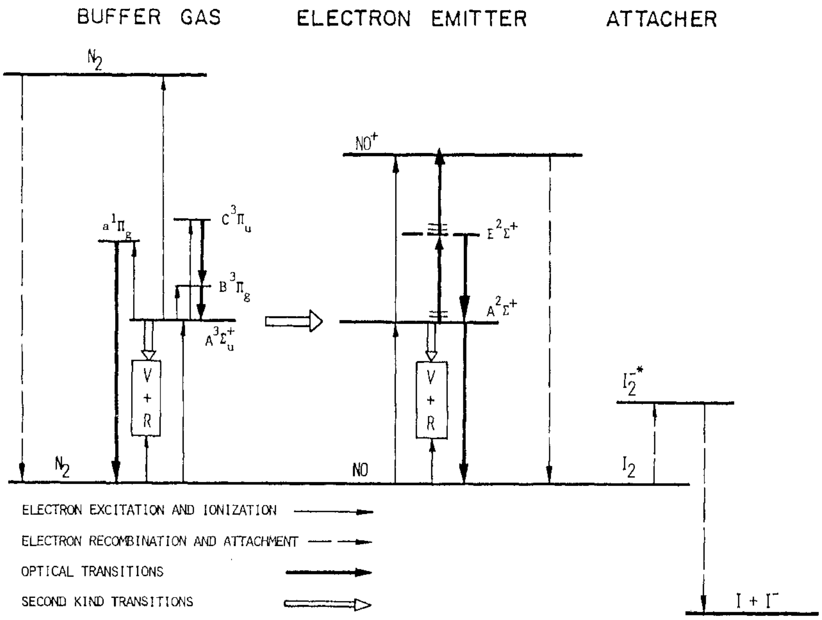

Fig. 5 Energy Level Diagram with Transition Mechanisms for a Lasers Controlled Opening Switch Gas Mixture

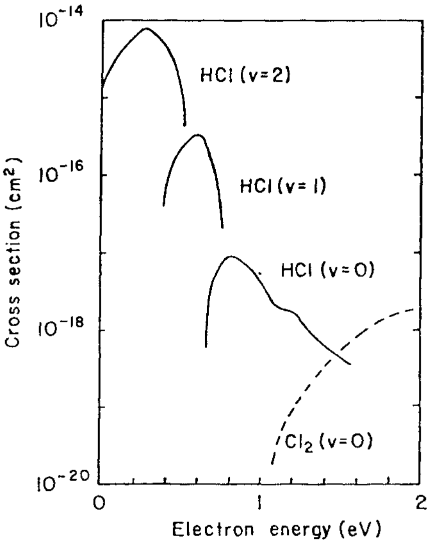

Fig. 6 Dissociative Attachment Cross Sections for Vibrationally Excited HCL Molecules [8]

Figure 7 shows a schematic energy level diagram, with transition mechanisms, for a gas system, which may be used for an attachment controlled opening switch. N_2 served as the buffer gas and is also the gas which is ionized. The attacher is "triggered" by means of an IR-laser, when the switch is to be opened. The discharge again has to be diffuse and cold. During the "on"-state the discharge can be either self-sustaining, but with low resistance, or sustained by means of an electron-beam or a second laser. The experimental arrangement described in one of the previous sections can also be used to test an opening switch concept, based on optical control of attachment cross sections.

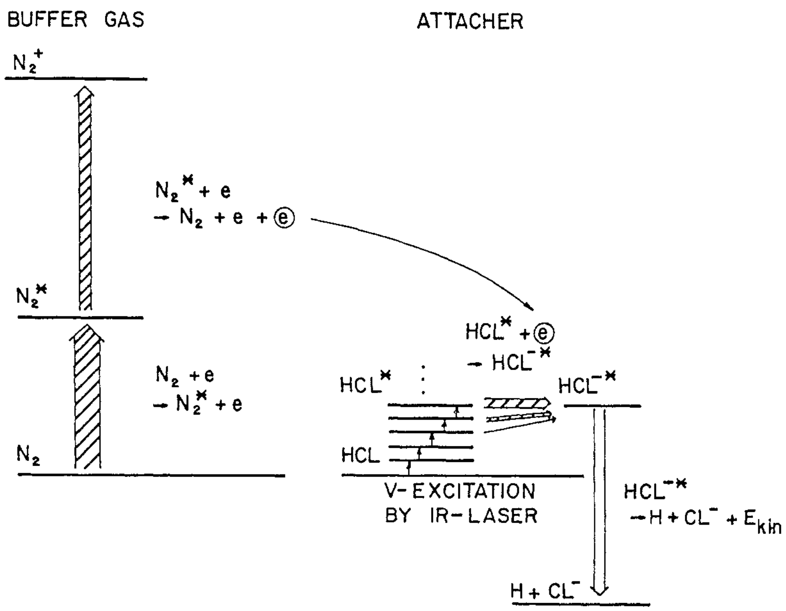

Fig. 7 Energy Level Diagram with Transition Mechanisms for a Gas Mixture with Optically Controlled Attachers

Summary

Using attachment processes to enhance the resistance of a diffuse discharge switch, opening times on the order of 10 ns should be possible. At the present time the rep-rate is probably limited mainly by the rep-rate of the laser used to control the switch.

Opening switches, where the opening effect is based on attachment are lossy, because a continuous energy supply is necessary to keep the electron density at a certain level. An improvement of their efficiency can be attained if attachers are used where the attachment cross section increases with reduced field strength. This effect is independent of the generation mechanism for the electrons. It can be used in electron-beam as well as in laser controlled switches. With lasers, however, resonance processes can be used for ionization. Losses due to excitation or scattering as in the case of electron-beam control are avoided, a fact, which may be important for high rep-rate opening switches.

A concept which can only be realized by means of lasers is that of enhancement of the attachment cross section by optical vibrational excitation of attachers. The efficiency should be high, because laser energy is used only during the opening phase, not to sustain the discharge.

References

1. J.K. Burton, D. Conte, R.D. Ford, W.H. Lupton, V.E. Scherrer, I.M. Vitkovitsky, Proc. of 2nd IEEE Intern. Pulsed Power Conf., Lubbock, Texas, p. 284 (1979).

2. R.F. Fernsler, D. Conte, and I.M. Vitkovitsky, IEEE Trans. on Plasma Science, 8, 176, (1980).

3. L.G. Christophorou, "Atomic and Molecular Radiation Physics" Wiley Interscience, John Wiley & Sons Ltd, p. 416 (1971).

4. W.E. Wentworth, R. George, H. Keith, J. Chem. Phys. 51, 1791 (1969).

5. Kaare J. Nygaard, IEEE J. Quantum Electr., 15, 1716 (1979).

6. H.C. Harjes, K.H. Schoenbach, M. Kristiansen, A.H. Guenther and L.L. Hatfield, IEEE Trans. on Plasma Science, 8, 1494 (1980).

7. J. Koppitz, J. Phys. D., 6, 1454 (1973).

8. H.L. Brooks, S.R. Hunter and K.J. Nygaard, J. Chem. Phys. 71, 1870 (1979).

9. W.L. Morgan and M.J. Pound, 33rd Gaseous Electronics Conf., Univ. of Oklahoma, Oct. 1980, Abstract FB-3.

10. M. Allan and S.F. Wong, J. Chem. Phys. 74, 1687 (1981).